Rates of compact binary mergers from LIGO/Virgo observations

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for the LIGO Scientific & Virgo Collaborations

LIGO Document G2100014-v3

LIGO – Virgo collaborations

LIGO Scientific Collaboration

LSC-Virgo O3 run : Where we are

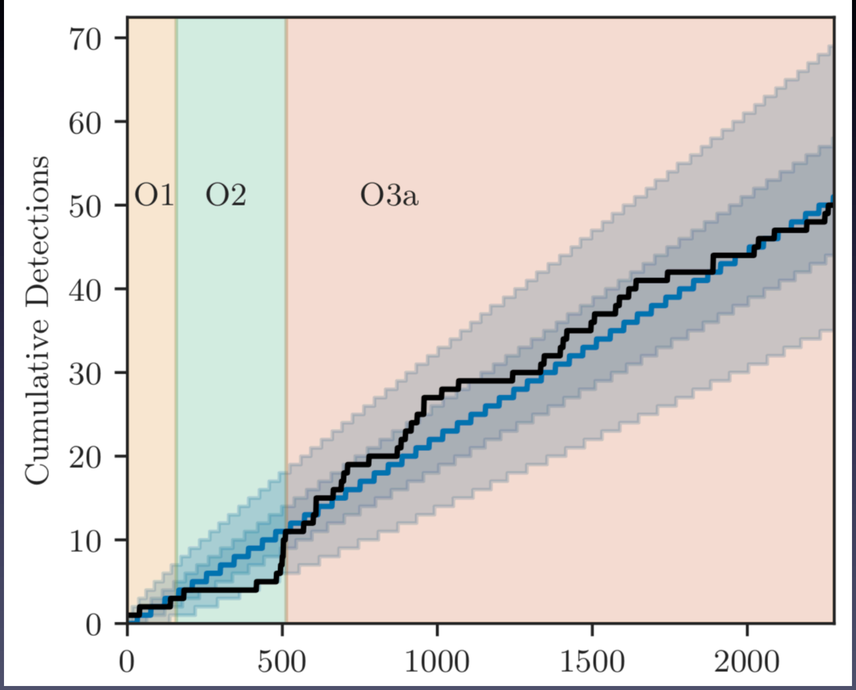
- O3 : 2019 Apr 1 – Oct 1 (O3a)
  Nov 1 – 2020 Mar 27 (O3b)
- Many GW signals !
- 'GWTC-2' : O3a catalog
  See talks of A. Effler,
  S. Sachdev in T01,

T01.00002: The LIGO Detectors: Sensitivity and Challenges
Invited Speaker: Anamaria Effler

T01.00003: Compact Binaries in Advanced LIGO and Virgo's Third Observing Run
Invited Speaker: Surabhi Sachdev

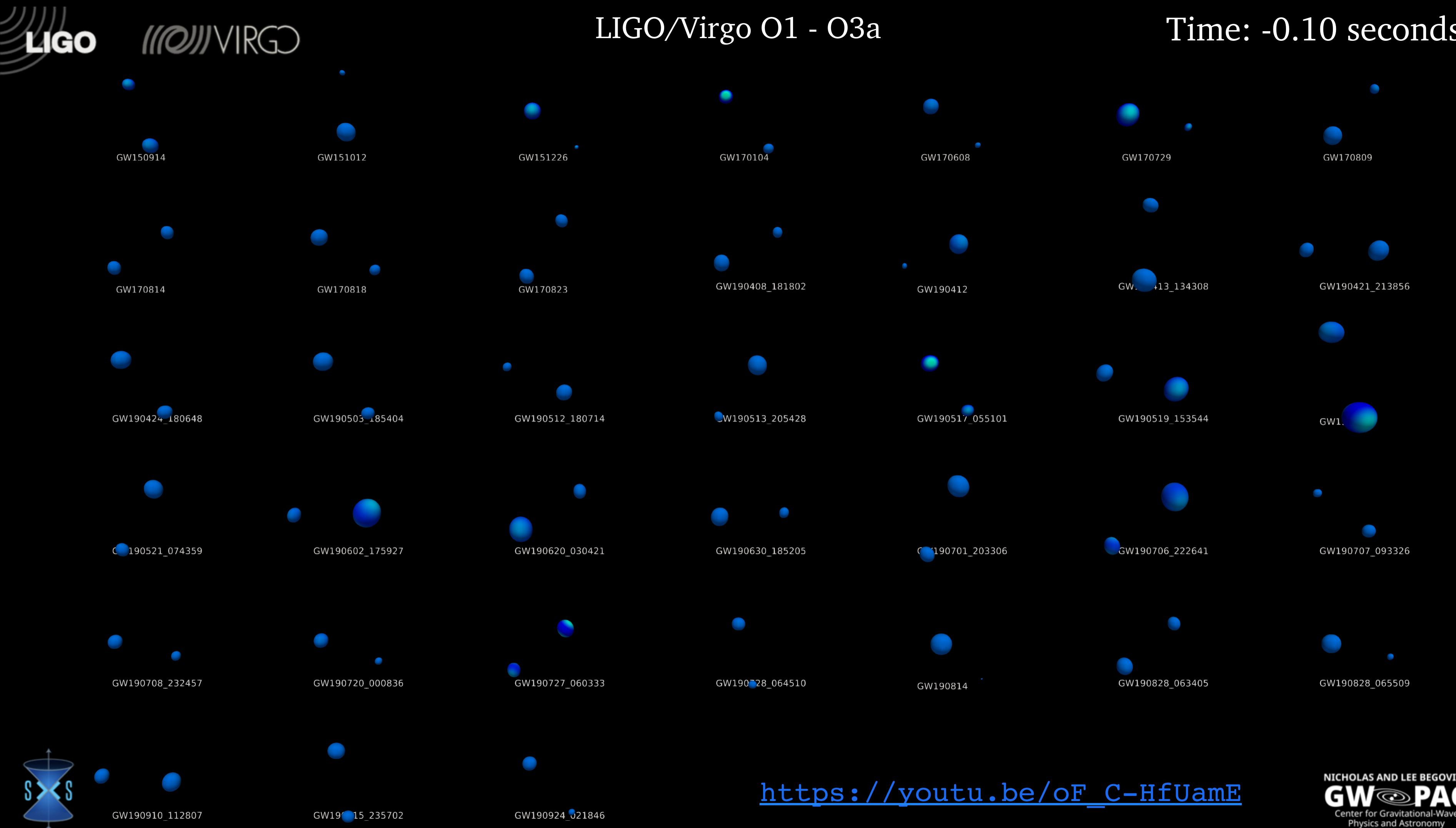
E01.00001: Tests of General Relativity with LIGO/Virgo
Invited Speaker: Maximiliano Isi

M.Isi in E01,
many other L-V related talks



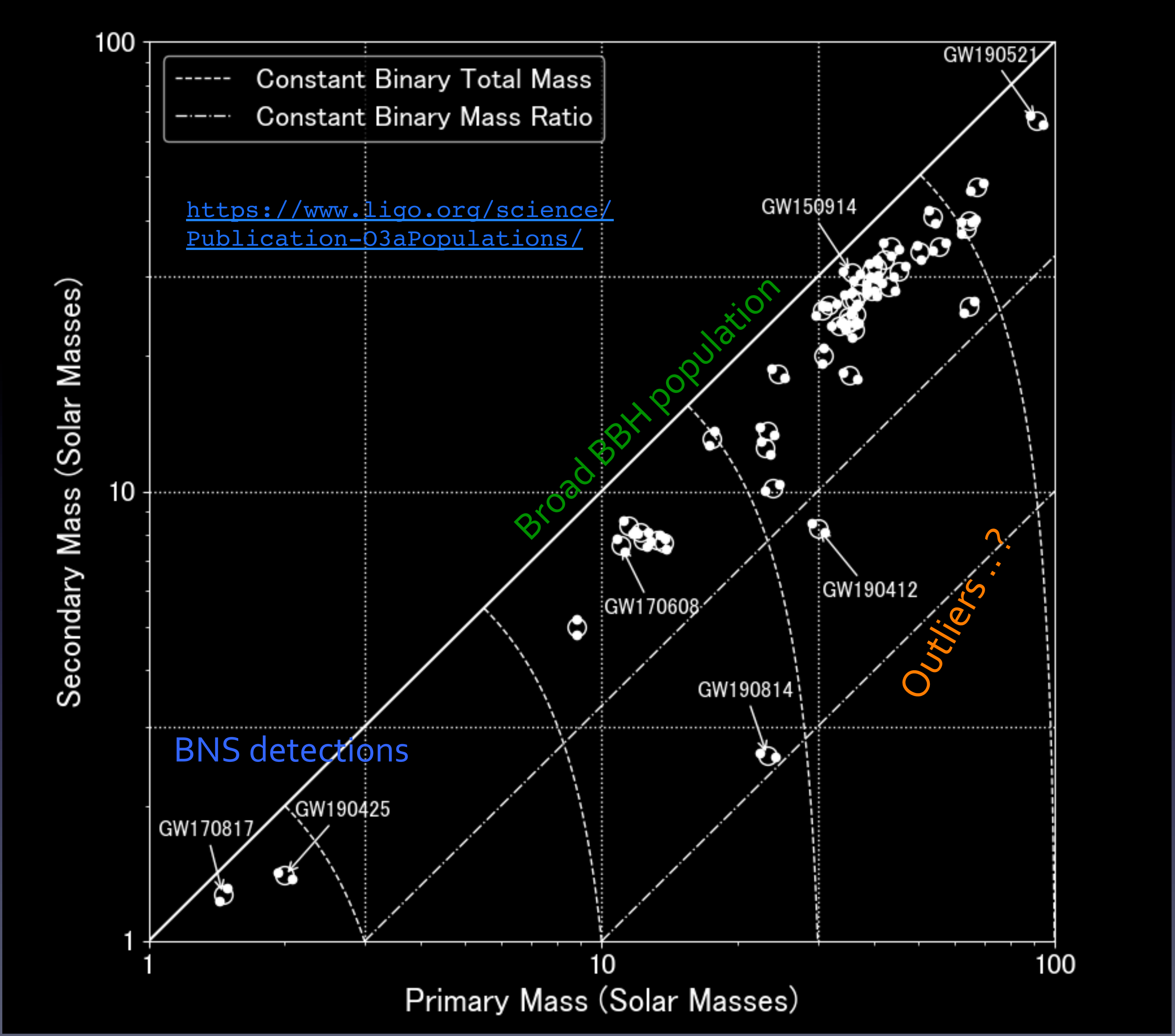
Approximate cumulative sensitivity
https://arxiv.org/abs/2010.14527

Signals are all binary mergers (so far)...



https://youtu.be/oF_C-HfUamE

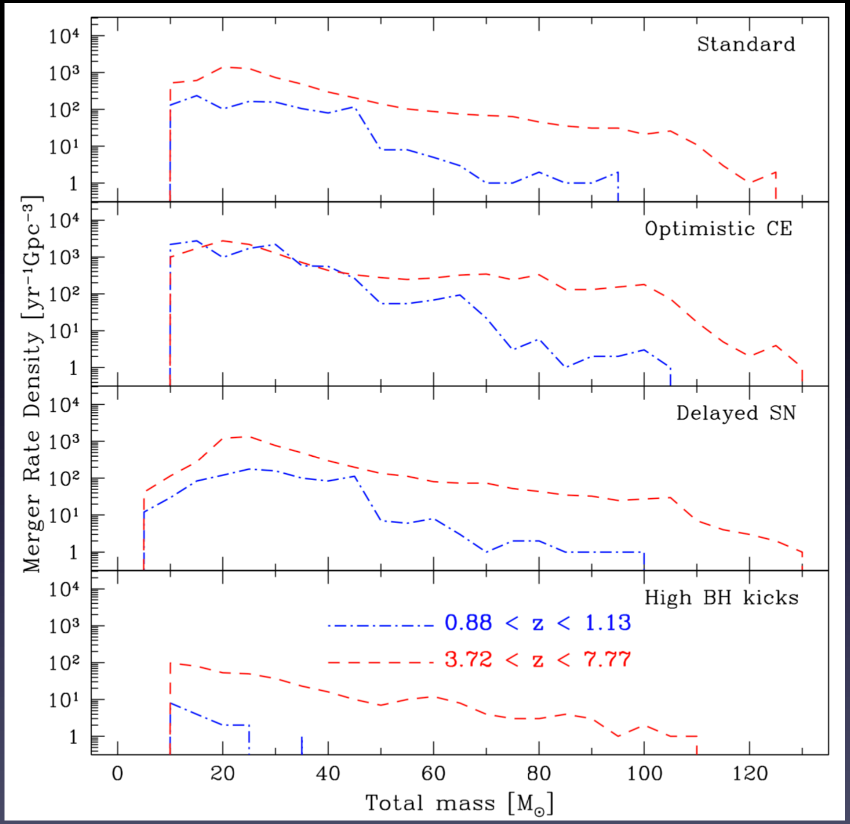
NICHOLAS AND LEE BEGOVICH GWPAC Center for Gravitational-Wave Physics and Astronomy



Constant Binary Total Mass
Constant Binary Mass Ratio
https://www.ligo.org/science/Publication-O3aPopulations/
Broad BBH population
Outliers …?
BNS detections
GW190521
GW150914
GW170608
GW190412
GW190814
GW170817
GW190425
Secondary Mass (Solar Masses)
Primary Mass (Solar Masses)
100
10
1

Astrophysical models vs. GW detections

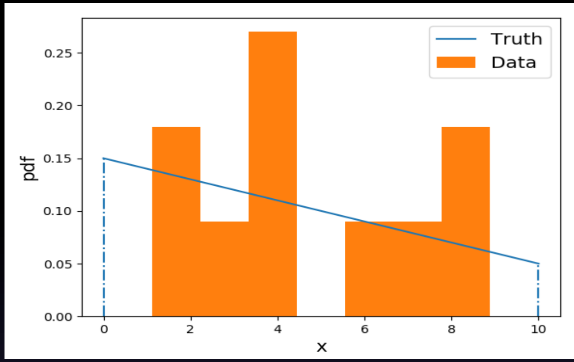
- Astrophysics modelling ⇒ *expected* merger distribution over redshift, masses, spins, …
- Models do not predict *individual* merger parameters
- GW detections ⇒ distribution 'samples'

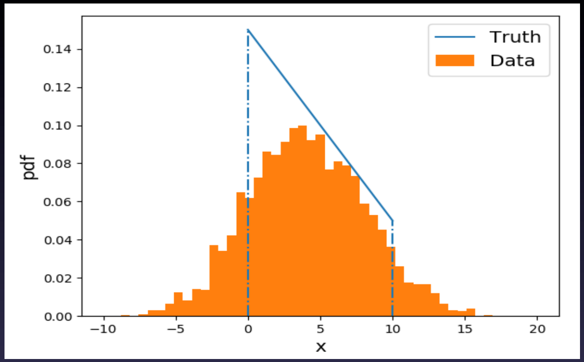


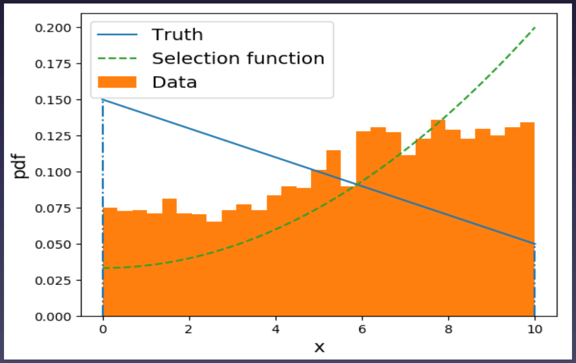
Dominik et al. Astrophys.J. 779 (2013) 72

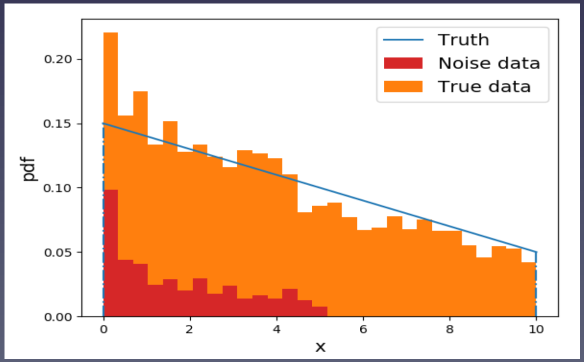
Hazards of GW population analysis

- Low # statistics
- Measurement error
- Selection bias
- Noise contamination



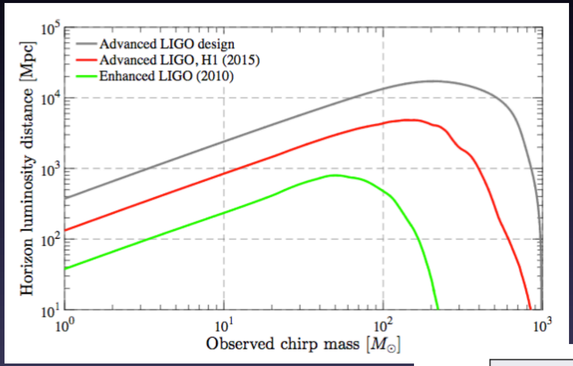






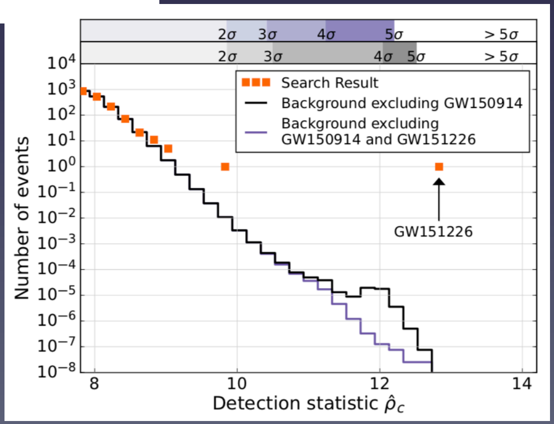
Strategies & solutions

- Simplified / ‘straw man’ models
- Bayesian hierarchical inference
- Search sensitivity estimation



LIGO, Phys. Rev. D 93, 112004 (2016)

- Search background estimation



LVC, Phys.Rev.X 6 (2016) 4, 041015

Strategies & solutions

- Simplified / 'straw man' models
  - in future we will have *large #* statistics
- Bayesian hierarchical inference
- Search sensitivity estimation

- Search background estimation

Compact binary merger parameters

- 2 × mass
- 6 × spin
- 3 × location (d/z, RA, dec)
- 3 × rotation (ι, ϕ, φ_c)
- Time of merger t_c

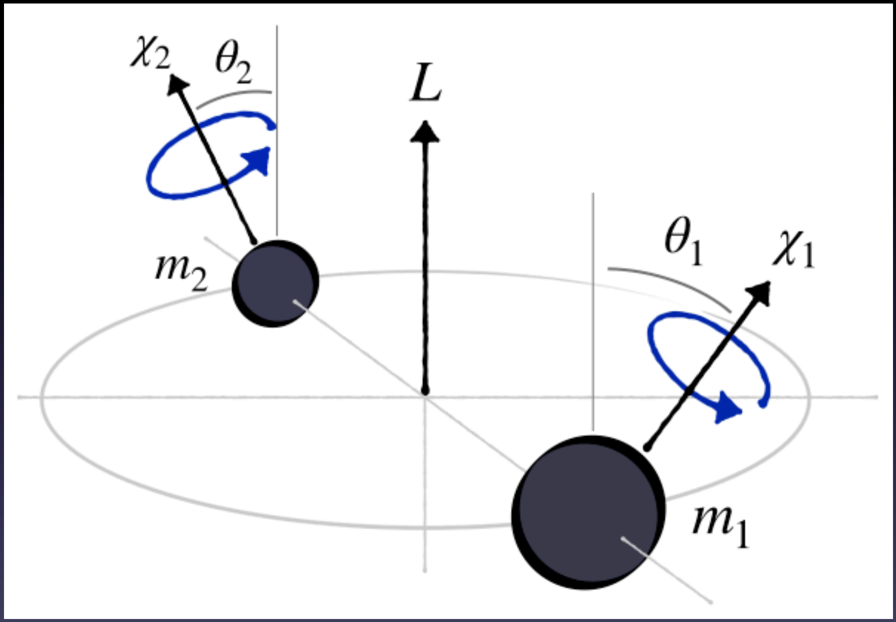


image credit : T. Callister

“Population properties of compact objects from [GWTC-2]”

Paper accepted, ApJL

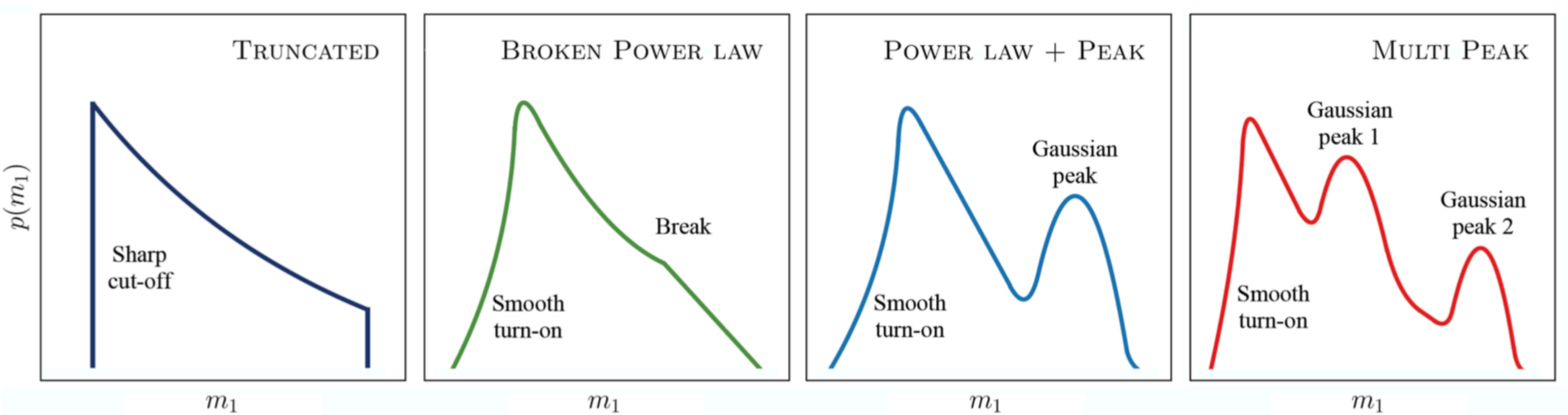
https://dcc.ligo.org/LIGO-P2000077/public

https://arxiv.org/abs/2010.14533

- Mass models & population properties
- Spin models & population properties
- Redshift dependence
- Summary rate estimates
- Outlier analysis

Mass models – power-law & beyond

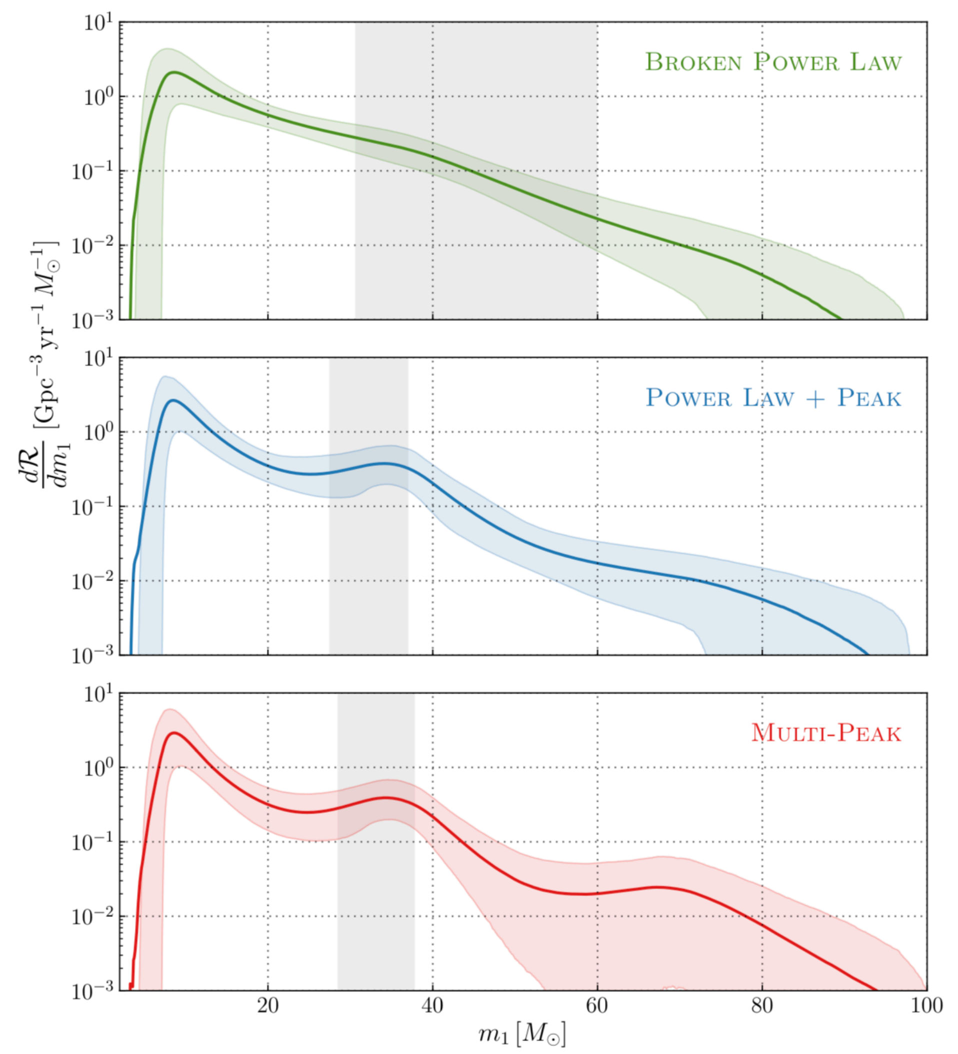
- Use simple 'straw person' models to *describe* data (not derived from astro modelling !)



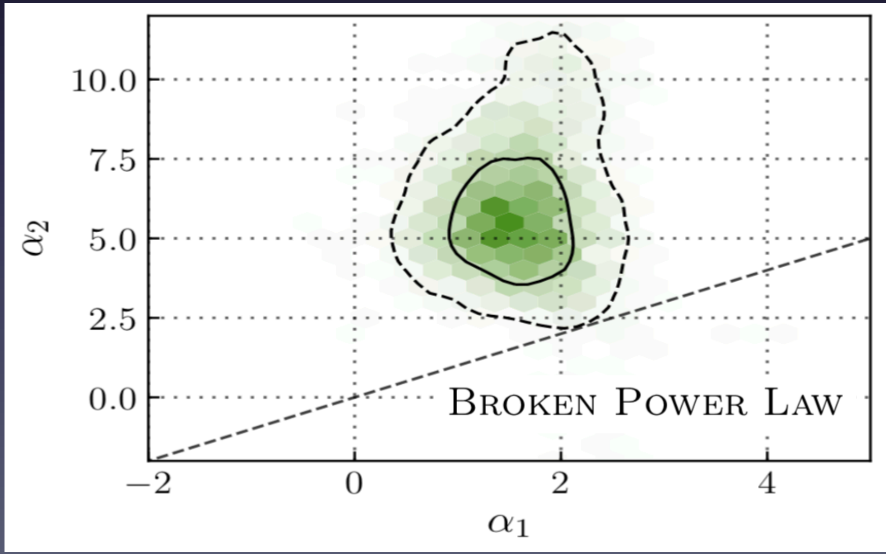
LVC, https://dcc.ligo.org/LIGO-P2000077/public

- O1-O2 results : p(m1) consistent with truncated power law, p(m2|m1) consistent with power law

BH mass spectrum has feature(s) !



Mass model	$\mathcal{B}$	$\log_{10}\mathcal{B}$
Power Law + Peak	1.0	0.0
Multi Peak	0.5	−0.3
Broken Power Law	0.12	−0.92
Truncated	0.01	−1.91
Power Law + Peak ($\delta_m = 0$)	0.87	−0.06
Broken Power Law + Peak	0.74	−0.13
Broken Power Law ($\delta_m = 0$)	0.35	−0.46
Power Law + Peak ($\lambda_{peak} = 0$)	0.05	−1.34



LVC, https://dcc.ligo.org/LIGO-P2000077/public

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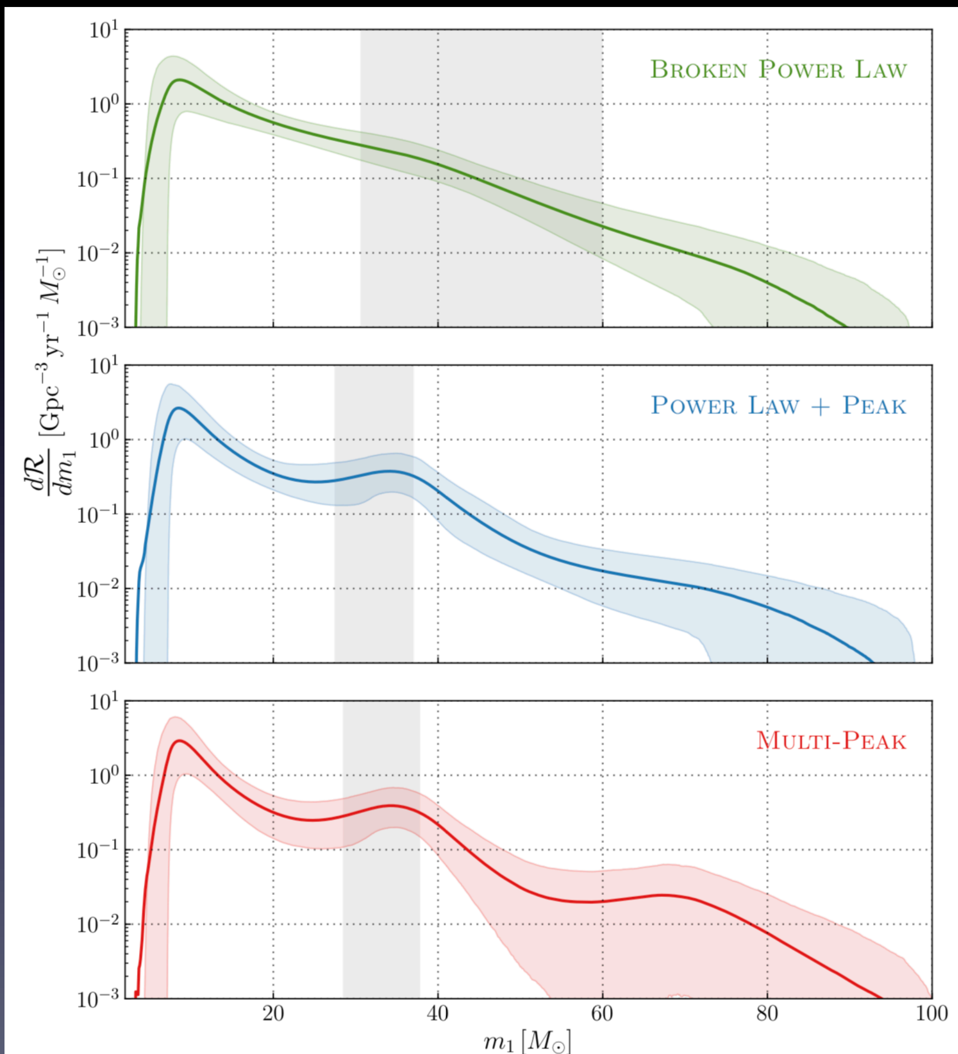

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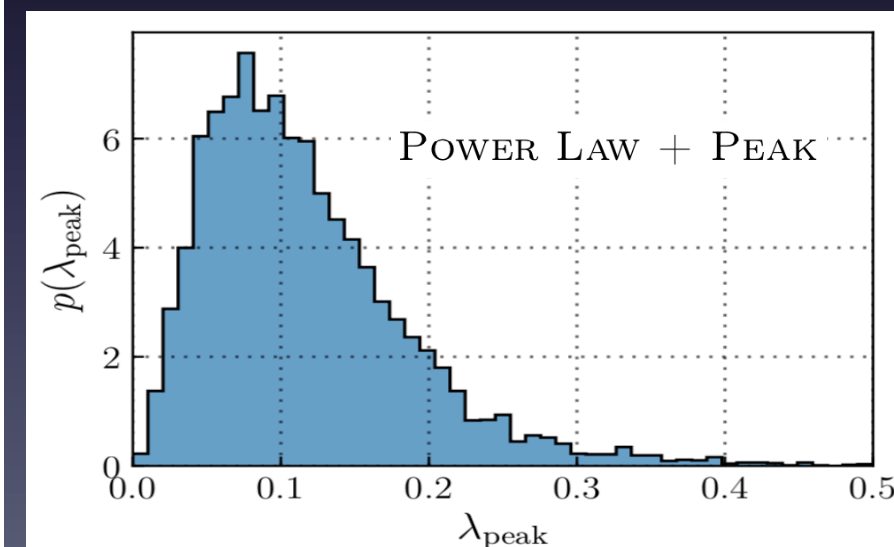
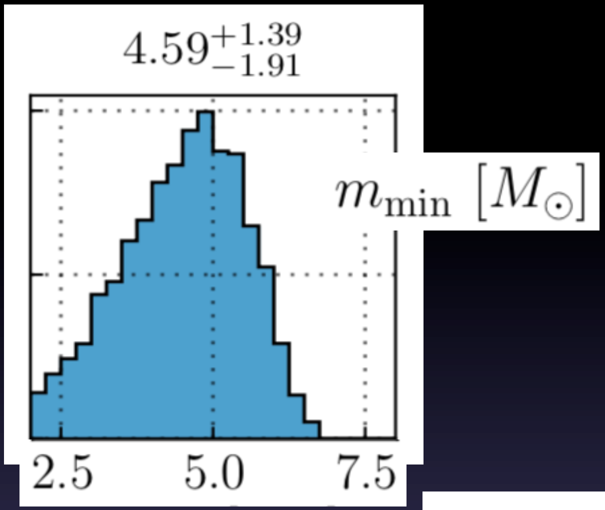


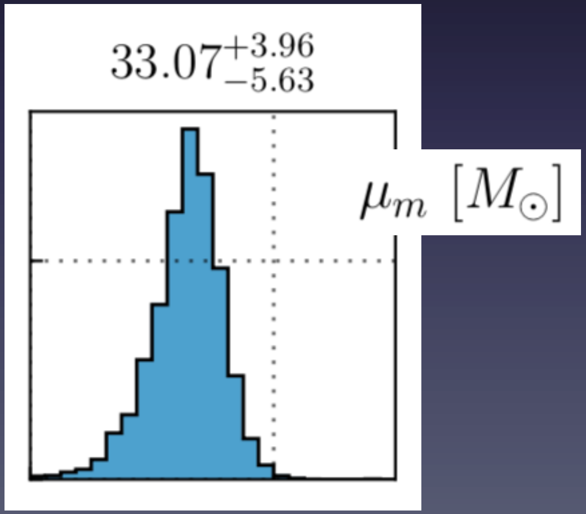
LVC, https://dcc.ligo.org/LIGO-P2000077/public

Mass spectrum parameters

- Minimum BH mass not well determined



- Gaussian peak centred @ 30-40 $M_\odot$



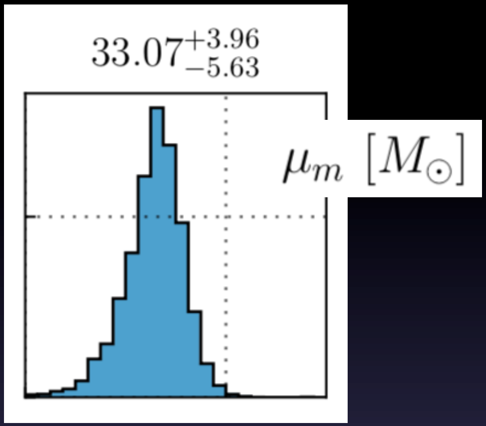
LVC, https://dcc.ligo.org/LIGO-P2000077/public

Mass spectrum parameters

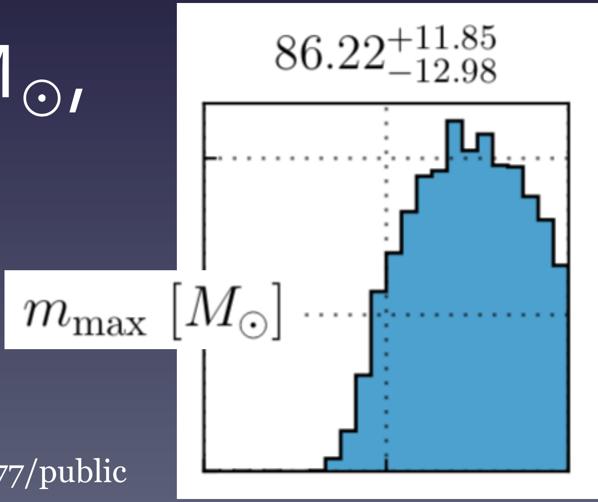
Astrophysical interpretation .. ?

bust against the choice of inclusion of GW190521. A "pile-up" of black holes at $M_{\text{pile-up}} \simeq 33\text{M}_\odot$ is robustly favored by this model. We are not aware of any mechanism that could produce a pileup in the mass function in this mass range.

Baxter et al. arXiv:2104.02685



- Maximum mass >~70 $M_\odot$, large uncertainty

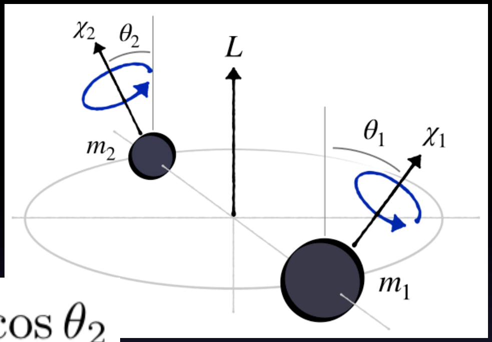


LVC, https://dcc.ligo.org/LIGO-P2000077/public

BH spin evidence

Spins affect GW signal in two ways

- Orbit-aligned spins speed up or slow down inspiral



$$\chi_{\rm eff} = \frac{\chi_1 \cos\theta_1 + q\,\chi_2 \cos\theta_2}{1+q}$$

- In-plane spins cause orbit to precess around total ang. mom.

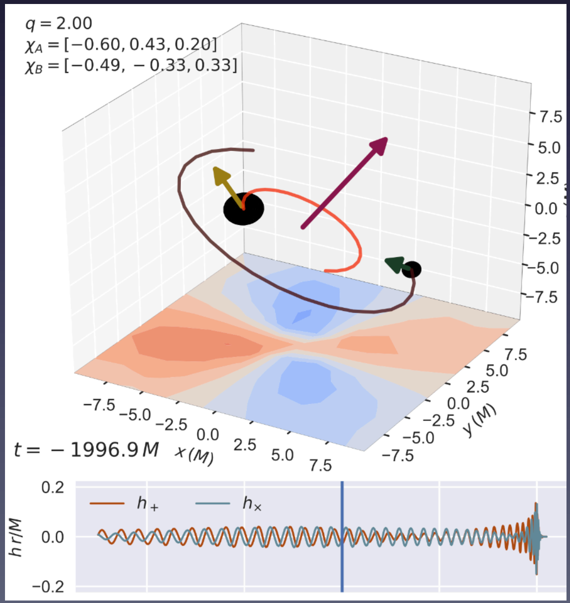
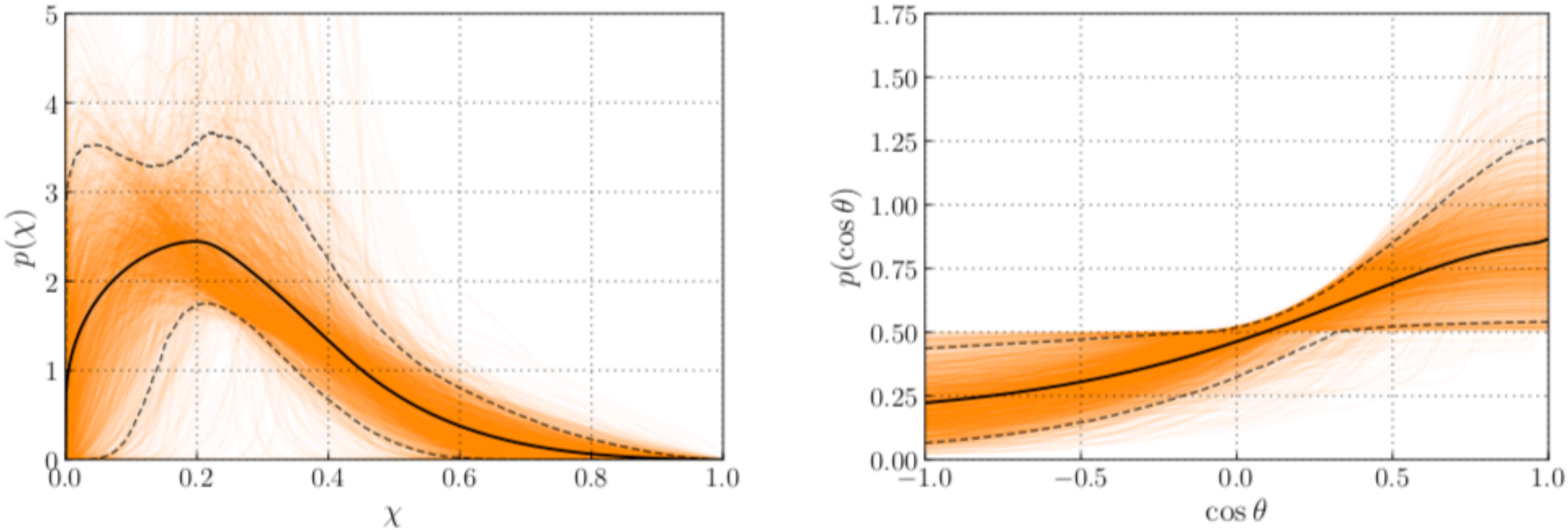


image credit: V. Varma

$$\chi_{\rm p} = \max\left[\chi_1 \sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q\,\chi_2 \sin\theta_2\right]$$

Schmidt, P., Hannam, M., & Husa, S. 2012, PhRvD

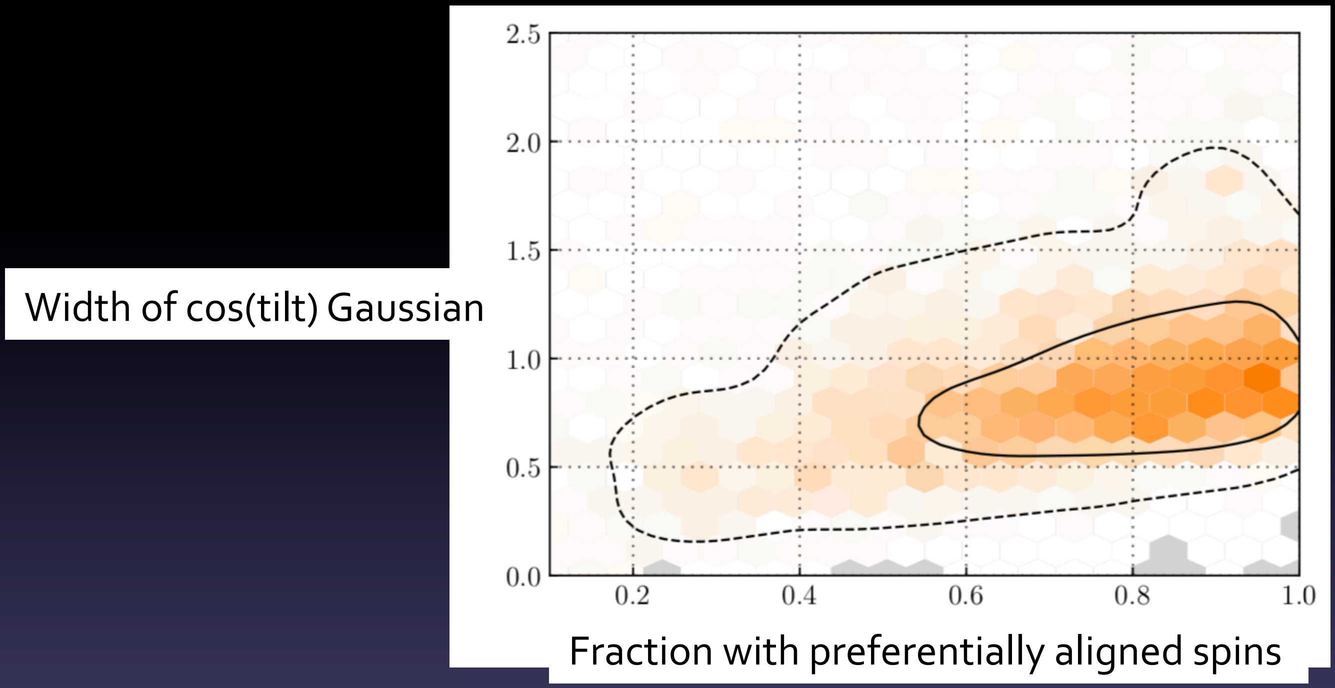
Spin magnitude / tilt inference



LVC, https://dcc.ligo.org/LIGO-P2000077/public

- Mostly small but nonzero spins
- Mostly small tilts (spins close to orbit-aligned) but *some* highly tilted / anti-aligned

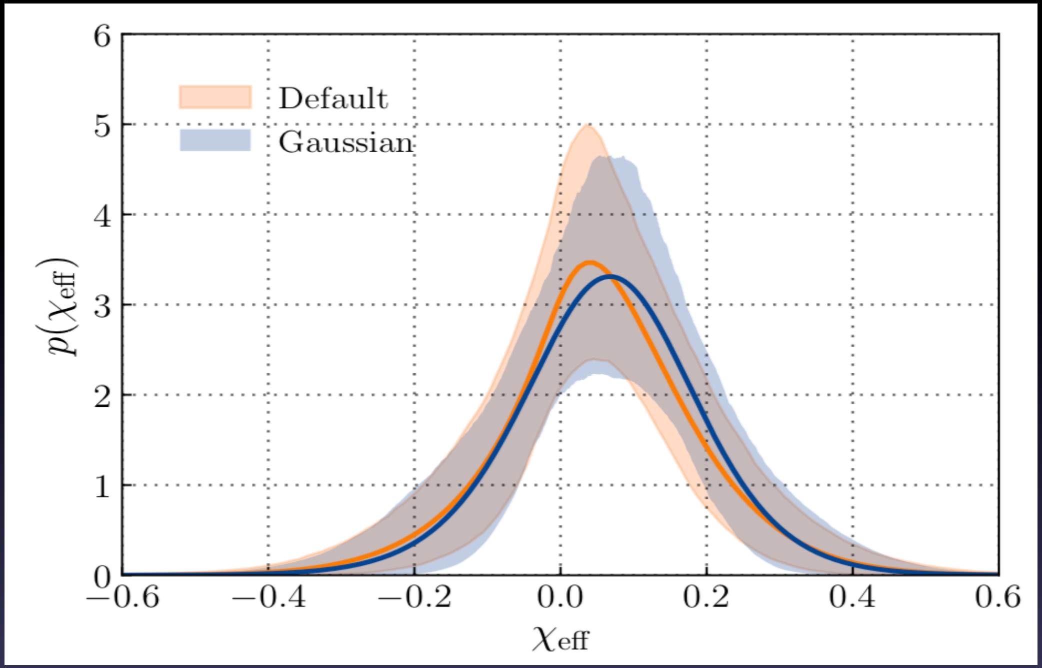
Evidence for in-plane (precessing) spin



LVC, https://dcc.ligo.org/LIGO-P2000077/public

- No *single* binary merger has strong evidence for $\chi_p > 0$
- May be caused by BH formation kicks (isolated binaries)
- or dynamical formation, or …

Evidence for tilts beyond 90°

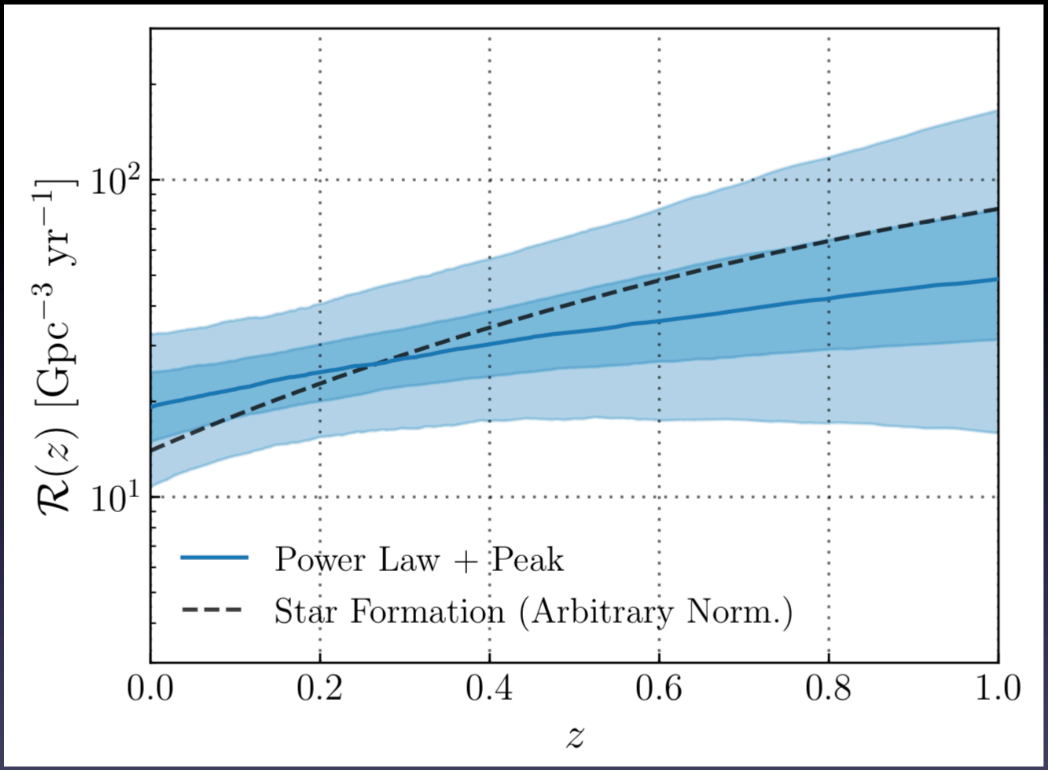


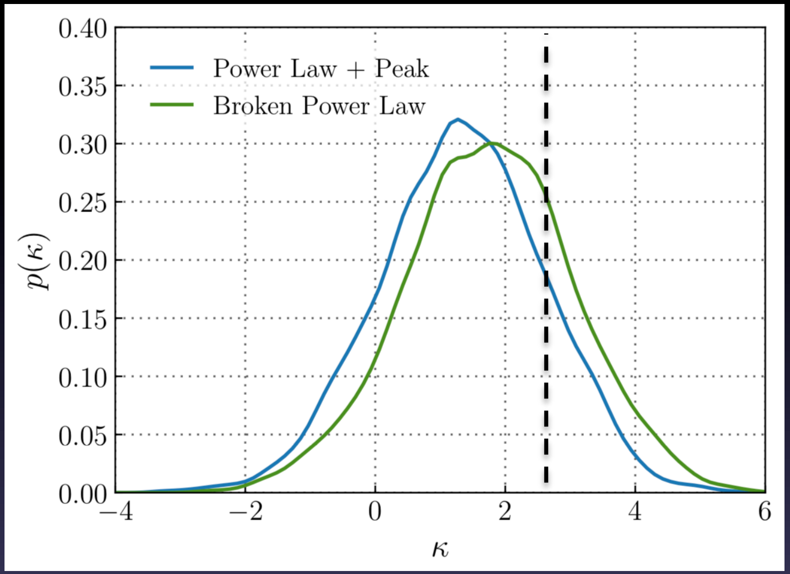
LVC, https://dcc.ligo.org/LIGO-P2000077/public

- $\chi_{\rm eff} < 0$ implies one or both spins *anti-aligned* with orbit
- ~12% to ~44% of binaries have such spins
- *Suggests* more than 1 formation channel active

  eg Zevin et al. Astrophys.J. 910 (2021) 2, 152

Redshift evolution





rate density scales like $(1+z)^{\kappa}$

LVC, https://dcc.ligo.org/LIGO-P2000077/public

- Comoving rate probably increases with z
- Probably more slowly than M-D SFR ~$(1+z)^{2.7}$

Merger rate summary

- BBH rate (constant comoving) $R_{\mathrm{BBH}} = 23.9^{+14.3}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
  - allowing redshift evolution $\mathcal{R}(z=0) = 19.3^{+15.1}_{-9.0}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- BNS rate assuming masses uniform on (1,2.5) $M_\odot$

$$R_{\mathrm{BNS}} = 320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

LVC, https://dcc.ligo.org/LIGO-P2000077/public

- NSBH rate limit (O1-O2) $610\ \mathrm{Gpc}^{-3}\ \mathrm{y}^{-1}$ LVC, Phys. Rev. X 9, 031040 (2019)

  (90% credible, 1.4+5 $M_\odot$ systems)
  - to be updated with O3 data in upcoming publications
- Other merger rate limits :
  IMBH, sub-solar mass, eccentric binaries …

LVC, Phys. Rev. D 100, 064064 (2019) LVC, Phys. Rev. Lett. 123, 161102 (2019) LVC, Astrophys. J. 883, 149 (2019)

Outlier analysis

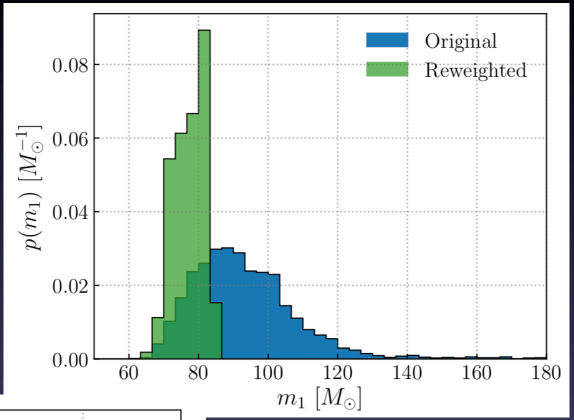
- Events with apparently ‘extreme’ mass parameters
  - Consider impact of population model (~prior) on measured event masses
  - Compare with most extreme *expected* event
  - Check if inferred population is consistent under inclusion/exclusion of event

GW190521 – the heaviest BBH

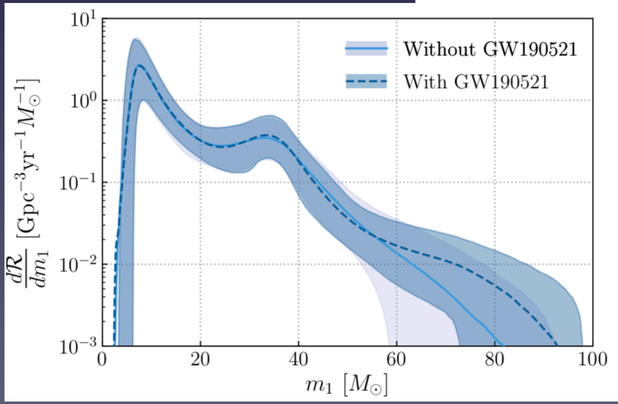
- Masses ($M_\odot$) $95.3^{+28.7}_{-18.9}$ $69.0^{+22.7}_{-23.1}$
  - remnant is first directly detected IMBH

LVC, *Phys.Rev.Lett.* 125 (2020) 10, 101102
& *Astrophys.J.Lett.* 900 (2020) 1, L13

- Apply population prior to mass measurement (Power-law Peak)



- BBH distribution with/without event consistent



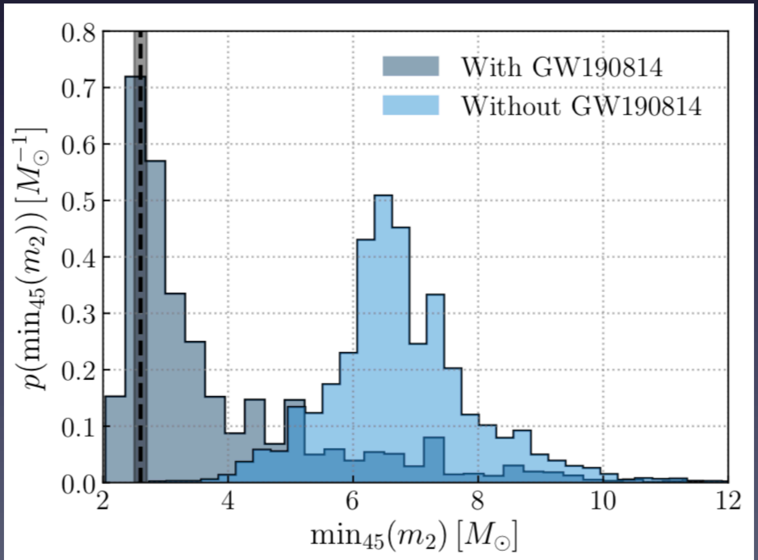
LVC, https://dcc.ligo.org/LIGO-P2000077/public

GW190814 – the 'mystery object'

- Primary ~23 $M_\odot$ BH, secondary 2.50–2.67 $M_\odot$
  - Either super-heavy NS or super-light BH

LVC, Astrophys.J.Lett. 896 (2020) 2, L44

- Clear outlier in secondary mass & mass ratio
- Probability <0.02% of seeing *as small* a m2 or m2/m1 over 45 events
- Indicates potential origin distinct from BBH population



LVC, https://dcc.ligo.org/LIGO-P2000077/public

Summary & outlook

- Detections up to O3a : ‘large’ BBH population but so far only hints at astrophysical features
- Excess of BBH with mass around 33 $M_\odot$
- Binary spins are not all orbit-aligned !
- 2 BNS ⇒ not yet a ‘population’
- GW190814 challenges usual classifications
- O3b : 5 more months at ~equal sensitivity
- O4 : 2022+, with KAGRA : watch this space !

LVC public data products

- GW Open Science Center data on GWTC-2

  https://www.gw-openscience.org/eventapi/html/GWTC-2/

Name	Version	Release	GPS ↓	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_\odot$)
GW190930_133541	v1	GWTC-2	1253885759.2	$12.3^{+12.4}_{-2.3}$	$7.8^{+1.7}_{-3.3}$	9.8	760^{+360}_{-320}	$0.14^{+0.31}_{-0.15}$	$20.3^{+8.9}_{-1.5}$

- Data release : population model samples, notebook to reproduce figures

PUBLIC LIGO DCC

LIGO Document P2000434-v2

Home Recent Changes Topics Login

Data Release for "Population properties of compact objects from the second LIGO-Virgo Gravitational-Wave Transient Catalog"

Document #: LIGO-P2000434-v2
Document type: P - Publications
Login to modify

Abstract:
This contains data products for LIGO-P2000077: "Population properties of compact objects from the second LIGO–Virgo Gravitational-Wave Transient Catalog"

For other relevant data products see:
https://dcc.ligo.org/LIGO-P2000223/public for parameter estimation results
https://dcc.ligo.org/LIGO-P2000217/public for the data product describing O3a detection sensitivity
(An estimate of the detector sensitivity for O1+O2, as used in the paper, is found below.)

The attached Jupyter notebook contains scripts to create all Figures in the text, aside from the Fig. 23 script which is found here: cwb_rnp_figs.zip. The relevant data read in by the notebook can be found on this page.

Other Versions:
LIGO-P2000434-v1
26 Feb 2021, 09:27

Files in Document:
- Jupyter notebook used to produce the figures in the text (Produce-Figures.ipynb, 2.2 MB)

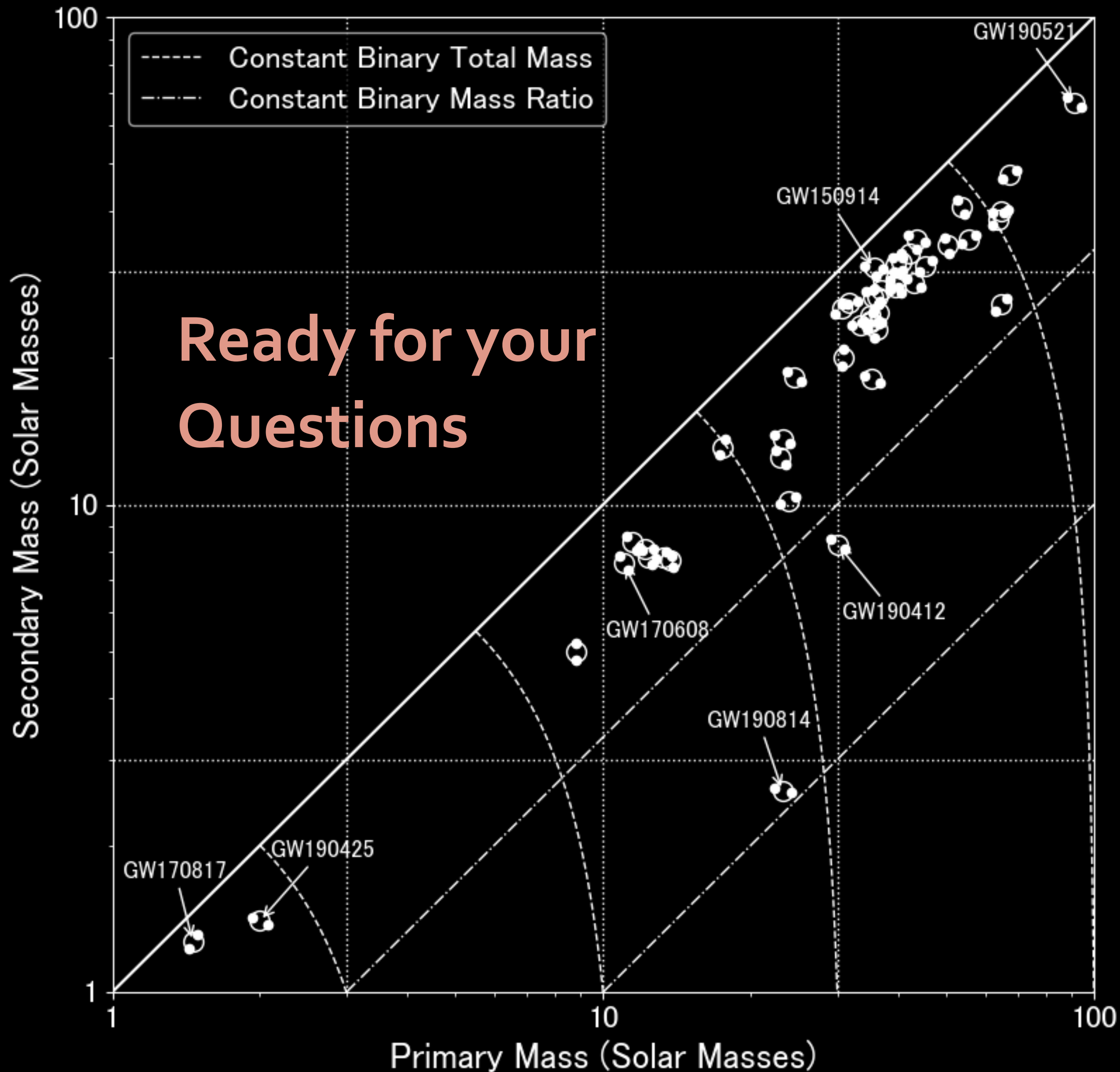
Other Files:
- Event_Samples.tar.gz (244.3 MB)
- Fig-10-spin-Reconstruction.tar.gz (232.8 MB)

https://dcc.ligo.org/LIGO-P2000434/public

Related Rate/Pop talks

- Daniel Wysocki - *Compact binary populations following O3a*
- Maya Fishbach - Cecilia Payne-Gaposchkin Award Finalist (2021): *LIGO-Virgo's Biggest Black Holes and the Mass Gap*
- Vicky Kalogera - *Filling in the Mass Gap: GW190814*
- Philippe Landry - *Distinguishing the Nature of the Lighter Compact Object in the Binary Merger GW190814*
- Gayathri V. - *The Heaviest Black Holes of LIGO/Virgo*
- Brendan O'Brien - *LIGO-Virgo binary black holes in the pair-instability mass gap*
- Salvatore Vitale - *New spin on LIGO-Virgo binary black holes*
- Vijay Varma - *Constraining recoil kicks for LIGO-Virgo binary black hole populations*
- Javier Roulet - *Characterizing the Population of Binary Black Holes with Detections of Arbitrary Significance*
- Nicholas DePorzio - *Distinguishing Black Hole Binary Formation Channels With Eccentricity Measurements and Other New Gravity Wave Probes*

Ready for your Questions



This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

BACKUP SLIDES

PowerLaw + Peak parameters

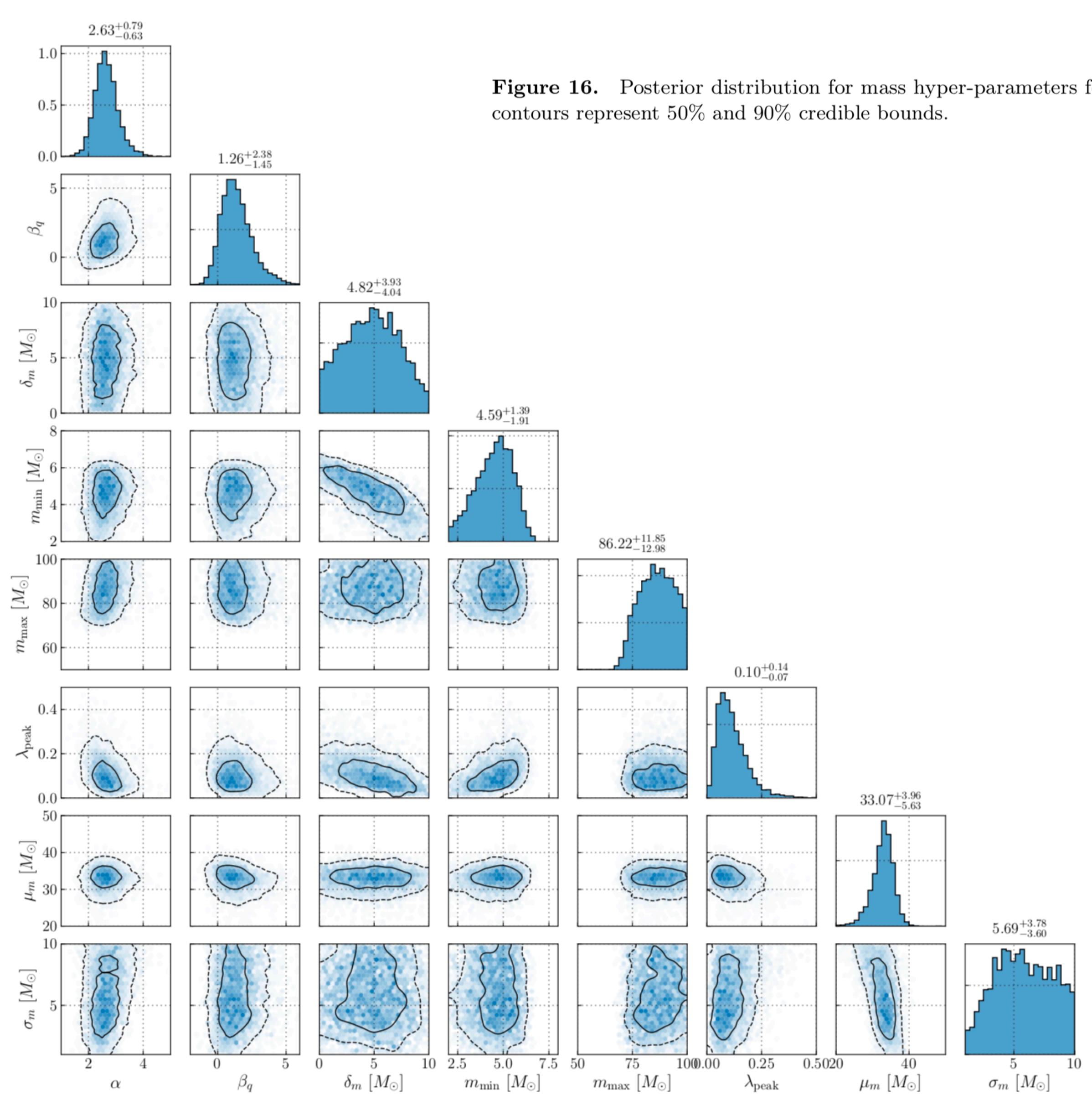
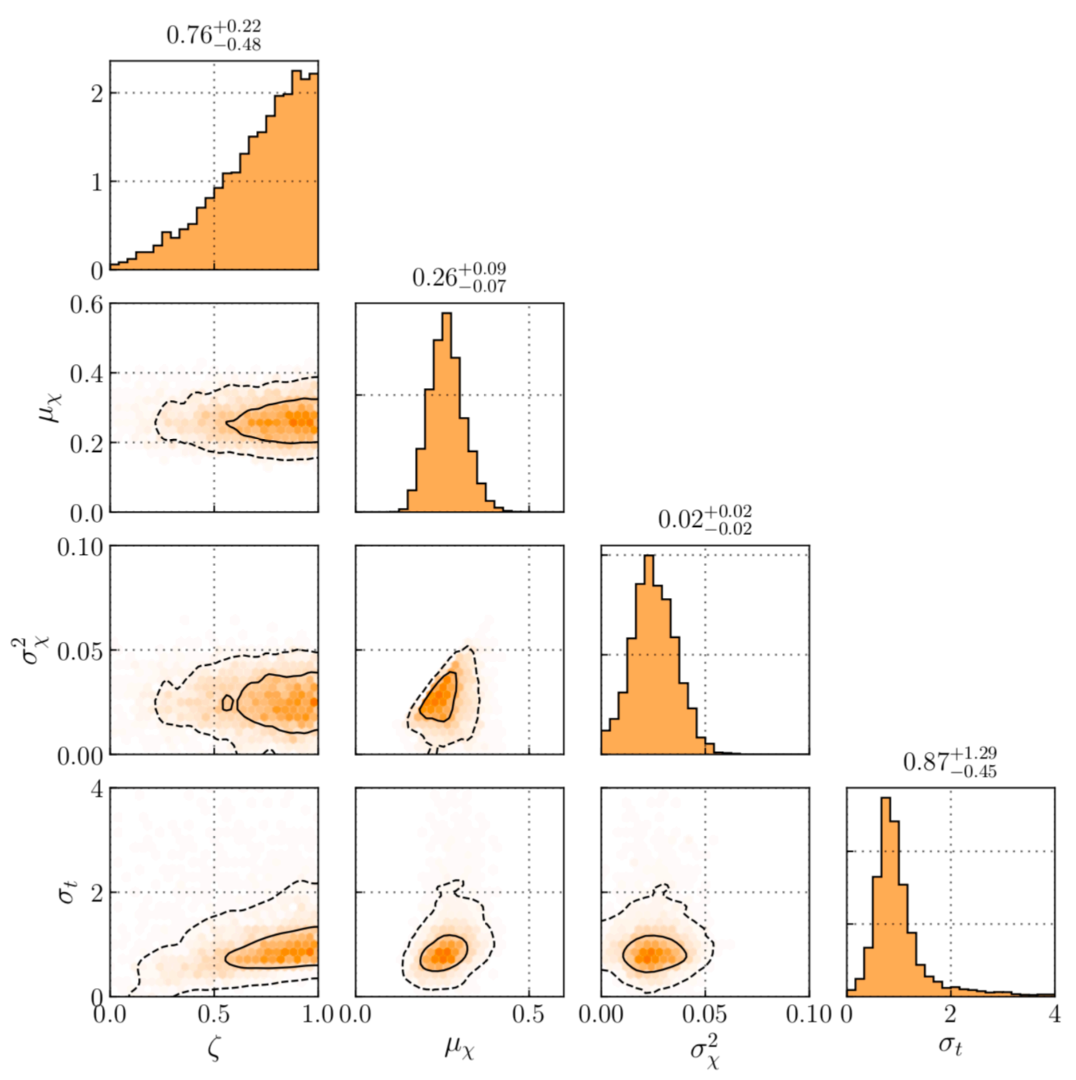


Figure 16. Posterior distribution for mass hyper-parameters for Power Law + Peak. The fit excludes GW190814. The contours represent 50% and 90% credible bounds.

https://dcc.ligo.org/LIGO-P2000077/public

‘Default’ spin model parameters



LVC, https://dcc.ligo.org/LIGO-P2000077/public

‘Default’ spin model

- Model spin magnitudes as Beta

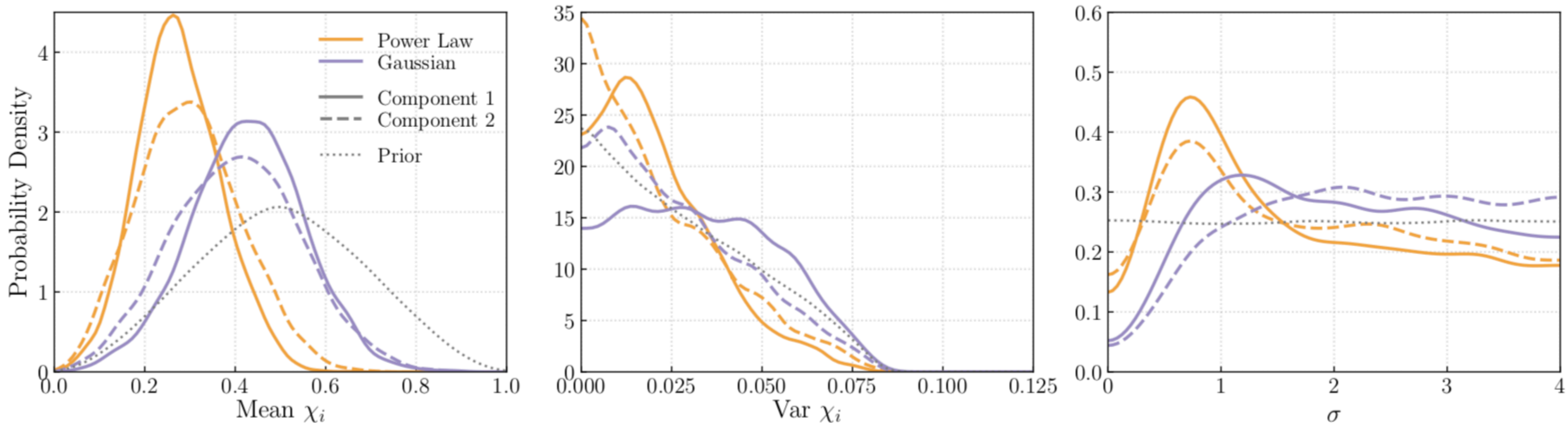
$$\pi(\chi_{1,2}|\alpha_\chi, \beta_\chi) = \mathrm{Beta}(\alpha_\chi, \beta_\chi)$$

- Tilts (cos θ) described by mixture :
  ζ * truncated Gaussian + (1 - ζ) * uniform

$$\pi(z|\zeta, \sigma_t) = \zeta\, G_t(z|\sigma_t) + (1-\zeta)\mathfrak{I}(z)$$

$$z = \cos\theta_{1,2}$$

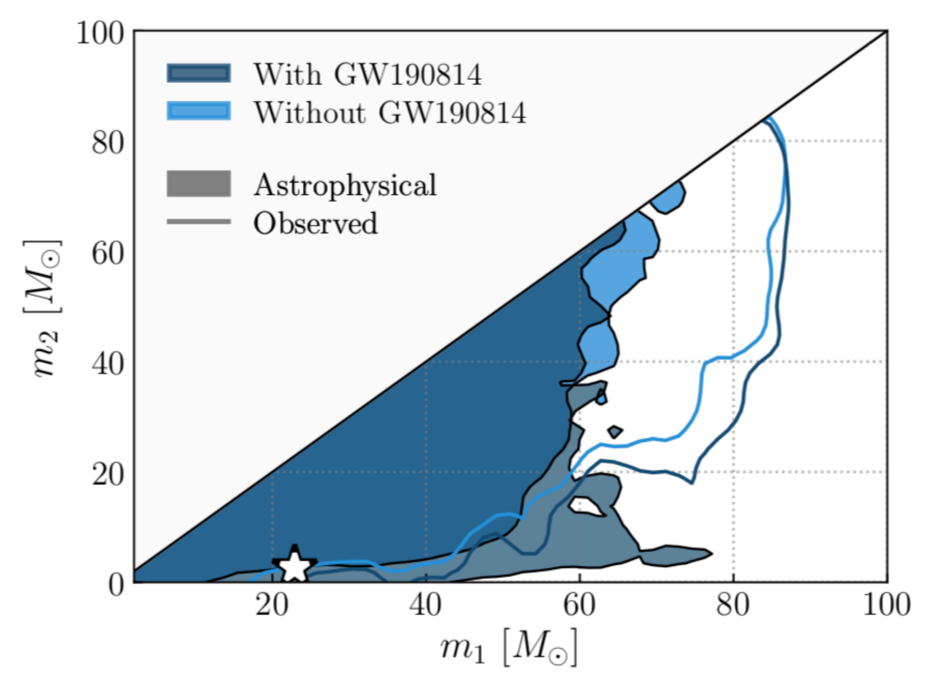
‘Multi Spin’ parameters



LVC, https://dcc.ligo.org/LIGO-P2000077/public

- Investigate whether spin properties depend on mass
- Also allow secondary spin to differ from primary
- Trends but no conclusive evidence

GW190814 masses



LVC, https://dcc.ligo.org/LIGO-P2000077/public

- m1-m2 values outside region covering expected detections (99%)